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1994 Written by R. H. Koebke of Tri-State University, Angola, Indiana and ARKAY Associates, Fremont, Indiana

ABSTRACT

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This case demonstrates that a simple compression force analysis is inappropriate when the loading or unloading process has an impulsive character.

R. H. Koebke

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The Problem

The new computer controlled work station was supposed to bend, twist, swage, perforate, and shear stainless steel flat wire stock. It accomplished all of this with great efficiency whenever it ran, but it often ran only for a few cycles before crashing when one or more of the three perforator punches would break in a peculiar manner. Perforators are small punching tools purchased in finished form like drill bits. They will wear as any tool does and are expected to be replaced periodically but not after only a few dozen working cycles. Fig.1 shows unused perforators and typical failed samples. We will refer to the entire small diameter section of the perforator as the point, the intermediate diameter section as the body, and the short large diameter end as the head. As Fig.1 shows, it was not the rather fragile looking and highly stressed point that failed, instead the more robust appearing head would break off. How was this possible?

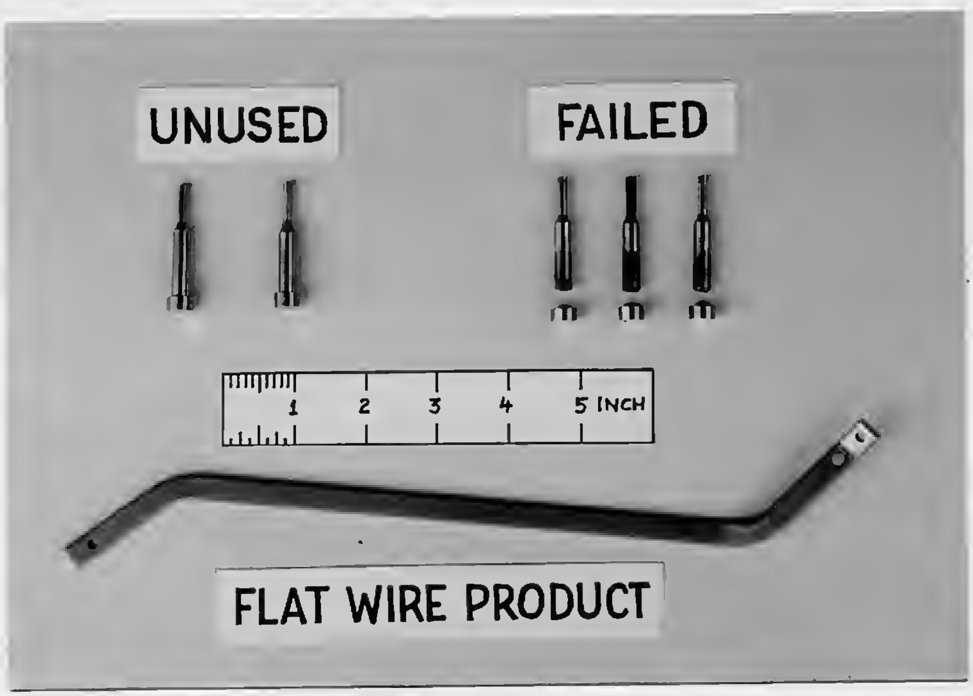

Fig. 1 Perforators and Perforated Product

It was initially thought that the perforator head separation might be caused an excessive tensile force generated on the up-stroke of the ram when the perforator point was withdrawn from the punched metal. In the absence of any analysis this explanation sounded reasonable since the process involved punching through metal thickness nearly equal to the hole diameter in tough stainless steel. However, the addition of set screws against the body to relieve the pull out force at the head was tried but accomplished nothing, the heads still broke off as before. Next, at considerable expense the tooling was changed to accept perforators of a larger body diameter. Unfortunately, to everyone's chagrin, the larger bodied perforators again failed in exactly the same manner. It was after this that I was asked to investigate.

Properties and Geometry of Perforators and Work Piece

PERFORATOR Material: M-2 tool steel; hardness: Rc= 65 at point, Rc= 55 to 60 in body; tensile yield strength (0.2% strain): approx. 280 kpsi; dimensions: point 0.150" dia.x 3/4" long, body 0.250" dia.x 27/32" long, head 0.370" dia.x 3/16" long, point to body fillet radius 0.438", body to head fillet radius 0.020"; geometric stress concentration factor at head fillet: K = 2.2.

WORK PIECE Material: cold formed stainless steel (300 series); tensile strength: approx. 180 kpsi estimated from hardness Rc = 30 to 40; dimensions: flat "wire" continuous strip, 3/8" wide x 0.125" thick.

Analysis and Solution

I began with a rough calculation showing that traction on the perforator point during withdrawal from the perforated metal would be insufficient to cause failure. As the fractured surfaces appeared to have some characteristics of a tensile fracture, it now became necessary to explain how tension might be generated by compression. Let me describe the dynamics of the perforating process. Initially the ram applies a very large static compressive force to the perforator while the workpiece tenaciously resists penetration. Then, suddenly, the metal ruptures allowing the perforator mass to accelerate forward. However, the forward acceleration must be arrested somehow by a backward directed impulse. It was now fairly clear that a backward impulse applied at the perforator head could create tensile forces at this location, but it was not immediately clear how to compute severity of this effect.

An alternate view of the dynamic events affecting a punch considers the unloading process of the statically applied compression. When a resisting force acting on the punch point is suddenly removed there is not an instantaneous relaxation of compression everywhere, rather, the load relaxation propagates from the point into the remainder of the punch in the form of a stress wave of opposite sign to the original compression stress. In the present case a simple compressive stress of the order of -420 kpsi existed in the punch point based on calculations taking into account material properties of the perforated metal and the geometry of the punch point. Consequently, upon unloading a tensile stress wave of magnitude +420 kpsi is launched at the point and begins to propagate into the punch body.

The theory of axial tension and compression stress waves in bars under the assumptions of a one-dimensional model may be found in references(*) discussing stress waves in elastic media. In the context of this theory our perforator point, body, and head comprise three wave guides in which extensional waves can freely propagate. However, at locations where sections of different diameters join, or at free ends, axial stress waves can not propagate without modifications. A wave incident upon such a discontinuity will be converted into two new waves, one of these is a reflected wave propagating backward and the other is a transmitted wave propagating forward. Moreover, the stress intensities of the new waves could be greater or of opposite sign to the original wave depending on the impedance of the discontinuity.

* R. W. Clough and J. Penzien; *Dynamics of Structures*; McGraw-Hill, 1975; Chapter 21.

The relevant stress relationships for this case are:

$$\sigma_i = -\sigma_o , \qquad \sigma_r = \frac{\alpha-1}{\alpha+1}\sigma_i , \qquad \text{and} \qquad \sigma_t = \frac{2}{\alpha+1}\sigma_i$$

Here α is the ratio of cross section areas at a discontinuity and the subscripts o, i, r, and t on the stress symbol σ denote initial, incident, reflected, and transmitted stresses. These stresses are in general functions of space and time of the form f(x-ct) or f(x+ct), that is, distribu- tions of axial stress which propagate forward or backward in the medium at speed c. For this analysis simple step shaped stress distributions suffice.

For our perforator the propagation effects of the unloading stress waves are illustrated in Fig.2. With reference to this figure, let me comment on the details shown there.

a. The initial stress distribution and the perforator model.

b. An unloading tensile stress wave σ_i of equal magnitude but opposite sign to the static compressive stress σ_o was incident at the free end. This forward travelling unloading stress wave σ_i momentarily reduces the total stress in the point to zero.

c. The stress wave σ_i was refracted at the point to body juncture into a forward travelling tensile stress wave σ_t transmitted into the body and a backward travelling reflected tensile stress wave σ_r which momentarily restresses the point.

d. The stress wave σ_r underwent total reflection at the free end into a forward travelling compressive stress wave σ_{rr}. The forward and backward travelling waves waves σ_r and σ_{rr} again momentarily reduce the total stress in the point to zero.

e. The stress wave σ_t was refracted at the body to head juncture into a forward travelling tensile stress wave σ_{tt} transmitted into the head and a backward travelling reflected tensile stress wave σ_{rt}.

The highest resultant stress was the static compressive stress of -420 kpsi in the point. It is indeed a rather high stress, but perforators loaded in simple compression are routinely subjected to such such stresses. The highest resultant tensile stress in the point was 198 kpsi due to the reflected tensile stress wave. In the body the highest nominal tensile stress was 154 kpsi due

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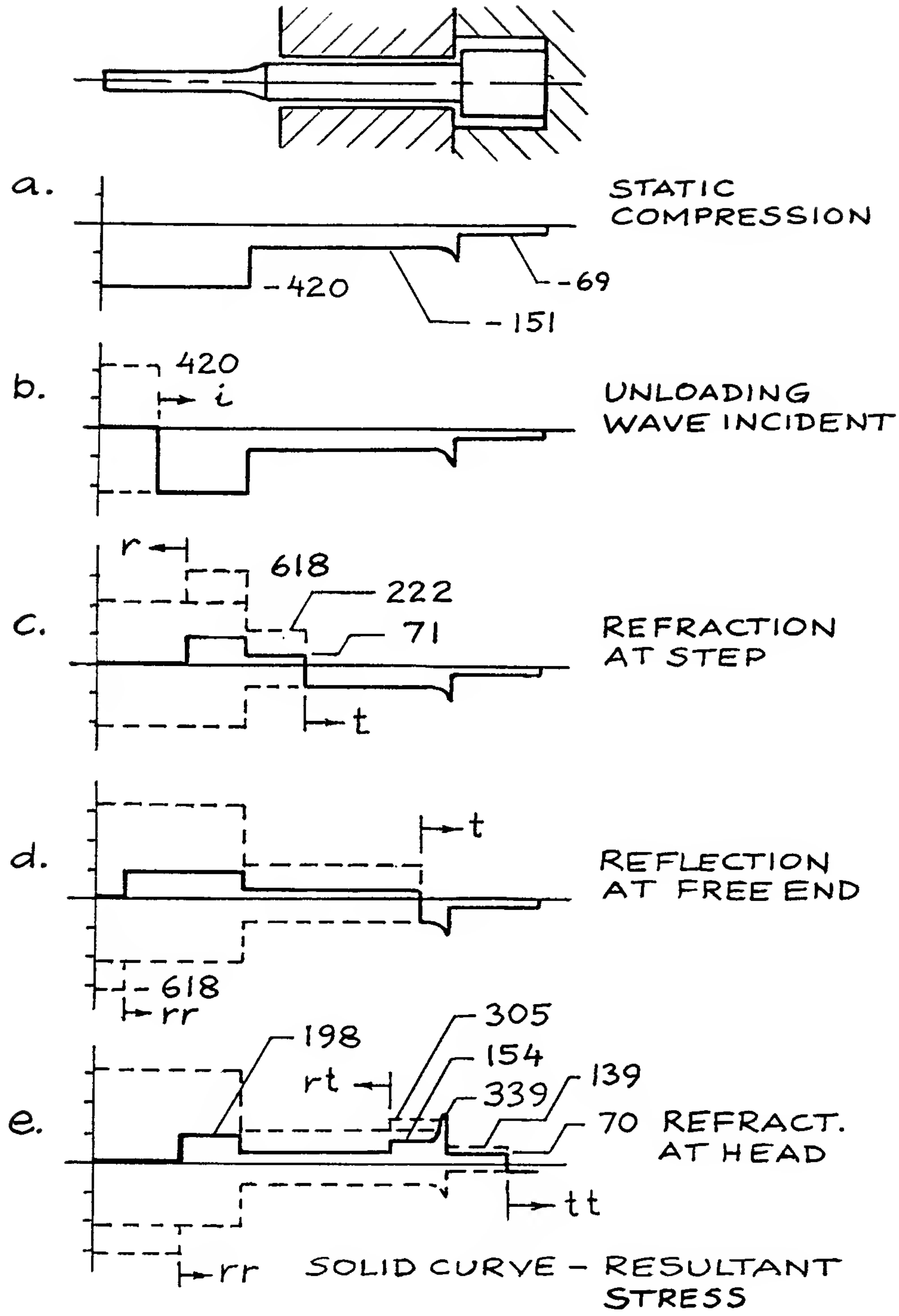

Fig.2 The Unloading Stress Waves (units are kpsi)

to reflection of the transmitted stress wave at the head. However, at the body to head juncture a stress concentration factor K=2.2 would apply on account of the abrupt change in section with a small fillet radius. Thus, the nominal body section stress of 154 kpsi was raised to a maximum of 339 kpsi at the head to body juncture which exceeded the material tensile yield strength, estimated to be about 280 kpsi, by 21%. I am confident that this tensile stress was the cause for the observed separation of the perforator heads. The analysis was not carried beyond wave refraction at the perforator head.

Some numerical data and stress sums leading to the results just described for 0.250" body diameter perforators are summarized below. Also listed below, but marked by a double asterisk (**), are other numerical data pertaining to modified perforators described in subsequent paragraphs.

STRESS WAVE REFRACTION COEFFICIENTS

Discontinuity	Area Ratio $\alpha = A^+/A^-$	Reflection $(\alpha-1)/(\alpha+1)$	Transmiss. $2/(\alpha+1)$
Point - Free End	0	-1	n.a.
Point - Body	2.778	0.471	0.529
Body - Head	2.190	0.373	0.627
Point - Body **	6.250	0.724	0.276

STRESSES AND RESULTANTS (kpsi)

Point

$\sigma_o = -420$

$\sigma_i = 420$

$\sigma_r = 0.471\sigma_i = 198$

$\sigma_{rr} = -1.0\sigma_r = -198$

$\sigma_o+\sigma_i+\sigma_r = 198$

$\sigma_o+\sigma_i+\sigma_r+\sigma_{rr} = 0$

Body

$\sigma_o = -151$

$\sigma_t = 0.529\sigma_i = 222$

$\sigma_{rt} = 0.373\sigma_t = 83$

$\sigma_o+\sigma_t = 71$

$\sigma_o+\sigma_t+\sigma_{rt} = 154$ nominal

$2.2(\sigma_o+\sigma_t+\sigma_{rt}) = 339$ with stress conc. factor 2.2

Head

$\sigma_o = -69$

$\sigma_{tt} = 0.627\sigma_t = 139$

$\sigma_o+\sigma_{tt} = 70$

Point **

$\sigma_o = -420$

$\sigma_i = +420$

$\sigma_r = 0.724\sigma_i = 304$

As a remedy for the head failure problem of the 0.250" body diameter perforators I suggested two modifications:

1. Removal of material from the perforator head leaving only a small annulus as a retaining shoulder. This reduces the body to head stress wave impedance by removal of mass from the head.

2. The creation of some deliberate but benign discontinuities in the smooth cylindrical perforator body by grinding of gently rounded notches at several locations. I speculated that these ought to disperse the wave fronts and thereby reduce the stress intensity at the body head juncture.

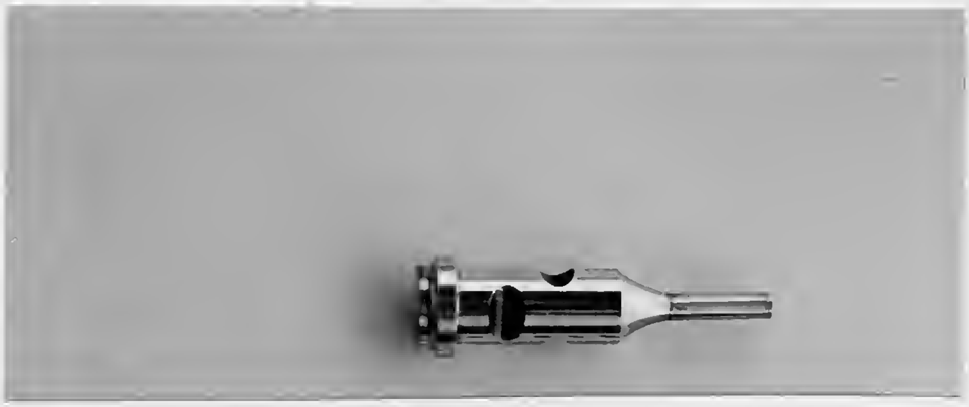

Fig. 3 A Modified Perforator

No modified perforators having body and head diameters as discussed in this analysis were made or tested, because, as I learned too late, the tool holders for the 0.250" body diameter size had been bored out to 0.375". Consequently, the modifications were implemented on larger bodied perforators for which the details of this analysis did not apply directly. When these larger bodied, modified perforators were finally run in the machine, none experienced head separation failure, but unfortunately, they now failed at the point body juncture. One should recall, as mentioned in the introduction, that unmodified, large bodied perforators were initially tried but failed at the head in the same way as the smaller size. In any case, the modifications to the 0.375" diameter perforators did indeed overcome the head separation problem, but now the large cross section area step from point to body had created a new problem. With hindsight, this new failure was also predictable since the tensile stress reflected from the point to body juncture into the point was now of the order of 304 kpsi. Regrettably the perforating operation as described here was subsequently terminated because production personnel believed that no reliable perforating punch could be designed. The holes in the product were then made by other means.

CHARLES O. SMITH
1920 COLLEGE AVENUE
TERRE HAUTE, IN 47803

(812) 232-7553

14 October 1994

Prof. Ralph H. Koebke
AEME
TriState University
P. O. Box 307
Angola, IN 46703-0307

Dear Prof. Koebke:

Enclosed is a revised, updated. corrected version of your PUNCH CASE with the two pages replaced. I think all is in order now.

Also enclosed is a reworked version of my letter of 3 October. I really "blew it" on the first version. I don't know what happened to my usually careful proof reading. If it buys you "brownie points" with the administration, great! I should point out that I have no idea how soon your case will appear in the Journal. Since that is a quarterly and there are a few digests already in the Editor's hands (in Germany), it may well be a couple of years before it sees print in the Journal.

Thanks for the additional copies of the photographs. We now have enough for two original copies of the Case (one in Terre Haute and one in Ottawa) and for the digest for the Journal.

I think all is in order at this point. If not, I'm sure you will not hesitate to let me (or Don Dekker) know. Many thanks.

Sincerely,

COS

C. O. Smith

CHARLES O. SMITH
1920 COLLEGE AVENUE
TERRE HAUTE, IN 47803

(812) 232-7553

3 October 1994

Prof. Ralph H. Koebke
AEME
TriState University
P. O. Box 307
Angola, IN 46703-0307

Dear Prof. Koebke:

On behalf of Don Dekker I have enclosed a copy of your PUNCH CASE with an "official" cover and the ECL number. We hope you like the looks of the case as it now appears in the Engineering Case Library. We would encourage you to consider another one!

I have another request. The International Journal of Engineering Education (a quarterly) is now publishing a "Case Digest" in each issue. This digest is a portion of a case (with some Editor's comments). The intent is to see what interest may be developed in cases in general, and a given case in particular. Geza Kardos (at Carleton University in Ottawa, Ontario) and I are the case digest editors. We would like to put your case in the Journal in digest form. We assume you have no objection since this will obviously call the attention of a large international audience to the case. To do this, however, we need more photographs. We would like two copies of Figure 1 and three copies of Figure 3 (the larger size).

Best wishes. I shall look forward to receiving the photographs. Thanks.

Sincerely,

C. O. Smith

cc: D. L. Dekker
RHIT

ARKAY ASSOCIATES
6530 N. Ray Road
Fremont, IN 46737

(219) 495-2165

October 9, 1994

Prof. Charles O. Smith
1920 College Avenue
Terre Haute, IN 47803

Dear Professor Smith:

I received your letter of October 3rd with enclosed ECL 280, my punch case. Thanks for your efforts in this matter. As to your suggestion to put this case into International Journal of Engineering Education, that would indeed be an honor, hence I am pleased if you would.

I am typing this letter at home to make sure it gets done and I am sending it to your home for similar reasons. Communications between universities are getting more cumbersome I find, telephone answering robots telling you to dial 1, dial 2, etc., then another answering machine and so on. Getting a letter typed and copied also seems to be a major undertaking around here.

There are a number of things I need to call to your attention:

1. Some time after I sent the final draft of the case to you, I discovered some minor typos, but I was not sure which draft I had actually sent. I tried to get in touch with Professor Dekker by telephone but was unsuccessful.

2. The enclosed xerox copy of my letter to Professor Dekker was sent by FAX in lieu of speaking to him by telephone, but I never heard anything. Perhaps our secretary forgot to send it, which is possible, but then again something else may have happened.

3. Upon seeing ECL 280, I of course noticed the typos are in it. It may be too late, but enclosed are two corrected pages.

4. Also enclosed are a copy of your letter to me of October 3rd. As this letter is quite important and useful to me for satisfying the university "bean counters", could you send me another one. Please look at the copy, you will see why.

5. I do not have additional prints of the photos that became Fig's 1 and 3 of the case, but I do have the negatives. On Monday, or as soon as I find time, I will have additional prints made and will send them to you.

6. Lastly, a few words about the punch case. It was just one of several things I did a few summers ago for ANCO of Michigan City, IN, the windshield wiper company. The parts shown in the photos and some personal notes are all I have; everything else is gone. The case story is told the way it really was, there are no additional records beyond what was cited in the case study. A very perceptive reader of the case might want to know details about the larger bodied, unmodified perforators that also failed by head separation. Sorry, I have no details!

Moreover, a few months after my summer work, ANCO underwent a change of ownership along with the attendant reshuffling of personnel and equipment. The people I knew when I was there are gone, and so is the punching robot. Consequently, no further information is obtainable.

Sicerely,

Ralph H. Koebke

Ralph H. Koebke

Enclosures: p.1 and p.4 of case (2 each)
FAX letter copy dtd. 9/28/94
letter copy dtd. 10/3/94

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3 October 1994

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